

single-photon frequency conversion and multi-mode entanglement via constructive interference on Sagnac Loop

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Based on constructive interference in Sagnac waveguide loop, an efficient scheme is proposed for selective frequency conversion and multifrequency modes W entanglement via input-output formalism. We can adjust the probability amplitudes of output photons by choosing parameter values properly. The tunable probability amplitude will lead to the generation of output photon with a selectable frequency and W photonic entanglement of different frequencies modes in a wide range of parameter values. Our calculations show the present scheme is robust to the deviation of parameters and spontaneous decay.

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I. INTRODUCTION

Quantum frequency conversion has been attracting attention as a potentially crucial resource in interfacing photonic quantum information systems working at disparate frequencies. Each kind of optical device has its own optimal frequencies which minimize the loss. For example, photon with wavelength around 800 nm is appropriate for the coherence optical memories with highest efficiency [1]. Recently, some works [2–8] demonstrate that the quantum character of the light field, such as entanglement and antibunching of light, is conserved during the process of quantum frequency conversion. This popularizes the use of frequency conversion in quantum information science, such as quantum repeaters, quantum memories, quantum key distribution, etc. In addition, quantum frequency conversion is widely employed in high-sensitivity detection of optical signals [9, 10] and single-photon source. So far, a great variety of methods [1–28] are provided for single-photon frequency conversion, like multiwave mixing [2–4, 15–18, 28], cavity opto-mechanics system [19, 20] and single-photon adiabatic wavelength conversion [21], and so on. More recently, a novel theoretical scheme is proposed for single-photon frequency conversion through constructive interference in Sagnac loop [22, 23]. We extend the constructive interference scheme to the realization of selective single-photon frequency conversion and multifrequency photonic entanglement, i.e., W entangled state [30], which has many inequivalent classes and cannot be transformed into each other under local operations and classical communication (LOCC) protocols. Thus, it is a crucial resource in quantum information science.

The present scheme has several important features. (1) The frequency of the output photon is adjustable by stark shift [31] and we can also elect the frequency of the output photon by adjusting parameters. In addition, the present scheme is capable of generating multifrequency photonic entanglement. (2) It does not require phase-matching on the involved frequencies of the optical fields although the similar multi- Λ model is employed in multiwave mixing process [25–27, 29]. Thus, we can choose the energy model widely for the present scheme. Note that tunable and selective wavelength conversion is described using fibre four-wave mixing [32], however the phase-matching condition is required. (3) The same probability amplitudes of the output photons will lead to the W entangled state of photons with different frequencies. In principle, it can be extended to the N mode photonic entanglement by choosing energy model and parameters properly.

II. THE MODEL

The model under consideration is illustrated in Fig. 1. It consists of a five-level atom coupling directly to a Sagnac waveguide loop. An external photon can go into the waveguide loop through a 50 : 50 beam splitter. On the waveguide loop, a phase shifter is used to adjusted the relative phase (Θ) between the clockwise and counterclockwise propagating pulses. As shown in Fig. 1(b) the atom has a multi- Λ -type level configuration, ground states $|0\rangle$ and $|e\rangle$, excited states $|1\rangle$, $|2\rangle$ and $|3\rangle$. Three continuous-wave

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(cw) Ω_1 , Ω_2 and Ω_3 are used, respectively, to driven resonantly the atomic transitions $|1\rangle \rightleftharpoons |e\rangle$, $|2\rangle \rightleftharpoons |e\rangle$, and $|3\rangle \rightleftharpoons |e\rangle$. Another three transitions $|0\rangle \rightleftharpoons |1\rangle$, $|0\rangle \rightleftharpoons |2\rangle$ and $|0\rangle \rightleftharpoons |3\rangle$ are driven by three quantum fields g_1 , g_2 and g_3 , respectively. In the interaction picture, the interaction Hamiltonian of the coupled system can given as ($\hbar = 1$) [33–35]:

$$H_I = \int_{-\infty}^{+\infty} \sum_{j=1,2,3}^{k=L,R} [\Delta_j a_{jk}^\dagger(\omega) a_{jk}(\omega) - g_j a_{jk}^\dagger(\omega) \sigma_{0j} - g_j a_{jk}(\omega) \sigma_{j0}] d\omega - \sum_{j=1,2,3} \Omega_j (\sigma_{je} + \sigma_{ej}), \quad (1)$$

where $\sigma_{mn} = |m\rangle\langle n|$ ($m, n = 0, 1, 2, 3, e$) are the transition operators between the quantum state $|m\rangle$ and $|n\rangle$. $a_{jL}^\dagger(a_{jR}^\dagger)$ means the

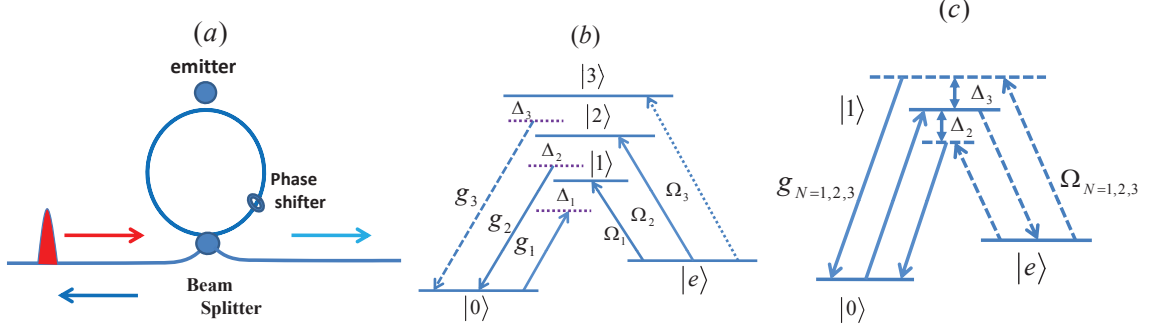


FIG. 1: (Color online) (a) Schematic of optical system. Sagnac waveguide loop connects to outside waveguide via Beam Splitter. On the waveguide loop, a phase shifter can be used to adjusted the relative phase between the clockwise and counterclockwise pulses; (b) A five-level multi- Λ system. Three excited states $|1\rangle$, $|2\rangle$ and $|3\rangle$; Two ground states $|0\rangle$ and $|e\rangle$. (c) A three-level multi- Λ system. One excited state ($|1\rangle$) and two ground states ($|0\rangle$ and $|e\rangle$).

creation operator for a left (right)-moving photon which drives the atomic transitions $|j\rangle \rightleftharpoons |0\rangle$. The creation and annihilation operators of the waveguide modes satisfy the commutation relation $[a_{jk}(\omega), a_{jk}^\dagger(\omega')] = \delta(\omega - \omega')$. The corresponding frequency detuning is $\Delta_j = \omega_{j0} - \omega$ and ω_{j0} is the frequency of transition $|j\rangle \rightleftharpoons |0\rangle$. When atom is initialed in the ground state $|0\rangle$ and the incoming photon only couples to the atomic transition $|0\rangle \rightleftharpoons |1\rangle$, we can describe the evolution of the system under consideration by the following wave function

$$|\Psi(t)\rangle = \int_{-\infty}^{+\infty} \sum_{j=1,2,3}^{k=L,R} c_{jk} a_{jk}^\dagger(\omega) |0\rangle |vac\rangle d\omega + \sum_{j=1,2,3,e} c_j |j\rangle |vac\rangle, \quad (2)$$

where $|vac\rangle$ is zero photon Fock state of the waveguide mode and c_j ($j = 1, 2, 3, e$) is the excitation amplitude of the atom in the state $|j\rangle$ ($j = 1, 2, 3, e$). c_{jk} ($j = 1, 2, 3$) is the amplitude for left ($k = L$)- or right ($k = R$)-moving photon of the waveguide mode when the atom is in the state $|0\rangle$. Using the Schrödinger equation $i \frac{\partial |\Psi(t)\rangle}{\partial t} = H_I |\Psi(t)\rangle$, we can obtain the time evolution of the amplitudes of the waveguide modes and atomic states are

$$i\dot{c}_{jk} = \Delta_j c_{jk} - g_j c_j, \quad (3a)$$

$$i\dot{c}_j = -g_j (c_{jk} + c_{j\bar{k}}) - \Omega_j c_e - i\gamma_j/2, \quad (3b)$$

$$i\dot{c}_e = - \sum_{j=1,2,3} \Omega_j c_j, \quad (3c)$$

where $j \in \{1, 2, 3\}$, and $\{k, \bar{k}\} \in \{L, R\}$ with $k \neq \bar{k}$. γ_j is the decay rate of the excited state $|j\rangle$ ($j = 1, 2, 3$).

In this optical system, the spontaneous decay through the path $|e\rangle \Rightarrow |1\rangle \Rightarrow |0\rangle$ can be greatly suppressed by the relative phase (Θ). When the relative phase is tuned to be zero, the incoming pulses propagating along opposite directions will form the spatial superposition and constructively interfere at the position of atom. Thus, combining with inherent symmetry of Sagnac waveguide loop, the physical system under consideration can be described by the following new operators:

$$a_{je(o)}(\omega) = \frac{1}{\sqrt{2}} [a_{jL}(\omega) \pm a_{jR}(\omega)], \quad (4a)$$

$$a_{je(o)}^\dagger(\omega) = \frac{1}{\sqrt{2}} [a_{jL}^\dagger(\omega) \pm a_{jR}^\dagger(\omega)], \quad (4b)$$

where $a_{je(o)}(\omega)[a_{je(o)}^\dagger(\omega)](j = 1, 2, 3)$ is the annihilation (creation) operator of the waveguide and the subscript $e(o)$ denotes the even (odd) waveguide mode in the Sagnac loop. In this case, the interaction Hamiltonian (1) can be rewritten as

$$H_I = \int_{-\infty}^{+\infty} \sum_{j=1,2,3} [\Delta_j a_{je}^\dagger(\omega) a_{je}(\omega) + \Delta_j a_{jo}^\dagger(\omega) a_{jo}(\omega) - \sqrt{2} g_j a_{je}^\dagger(\omega) \sigma_{0j} - \sqrt{2} g_j a_{je}(\omega) \sigma_{j0}] d\omega - \sum_{j=1,2,3} \Omega_j (\sigma_{je} + \sigma_{ej}), \quad (5)$$

and the wave function (2) is

$$|\Psi(t)\rangle = \int_{-\infty}^{+\infty} \sum_{j=1,2,3}^{k=e,o} c_{jk} a_{jk}^\dagger(\omega) |0\rangle |vac\rangle d\omega + \sum_{j=1,2,3,e} c_j |j\rangle |vac\rangle, \quad (6)$$

where

$$c_{je(o)}(\omega) = \frac{1}{\sqrt{2}} [c_{jL}(\omega) \pm c_{jR}(\omega)], \quad (7a)$$

$$c_{je(o)}^\dagger(\omega) = \frac{1}{\sqrt{2}} [c_{jL}^\dagger(\omega) \pm c_{jR}^\dagger(\omega)], j = 1, 2, 3. \quad (7b)$$

The above Hamiltonian (5) reveals that only the even mode experiences frequency conversion and the frequency of odd mode remains unchanged. In fact, when $\Theta = 0$, only the even waveguide mode propagates in the Sagnac loop [22, 23]. Integrating the differential Eq. 3(a), and substituting c_{jk} into Eq. 3(b), we can obtain the coupling equations connecting the input and output pulses

$$\dot{c}_j = -2\pi g_j^2 c_j + i2\sqrt{\pi} g_j c_{je}^{in} + i\Omega_j c_e, (j = 1, 2, 3) \quad (8a)$$

$$\dot{c}_j = 2\pi g_j^2 c_j + i2\sqrt{\pi} g_j c_{je}^{out} + i\Omega_j c_e, (j = 1, 2, 3) \quad (8b)$$

where $c_{je}^{out(in)} = \frac{1}{\sqrt{2}}(c_{jL}^{out(in)} + c_{jR}^{out(in)})$ ($c_{jk}^{in} = \int_{-\infty}^{+\infty} c_{jk}(0)e^{-i\Delta_j(t-t_0)} d\Delta_j$ and $c_{jk}^{out} = \int_{-\infty}^{+\infty} c_{jk}(0)e^{-i\Delta_j(t-t_1)} d\Delta_j$ ($j = 1, 2, 3$ and $k = L, R$) correspond to the input and output waveguide modes, respectively.). Here, we have set the condition $t_0 < t < t_1$. $c_{jk}(0)$ is the initial value of the amplitudes c_{jk} at $t = t_0$. According to Eqs. 8(a)-(b), we can obtain the input-output formalism [36, 37] as

$$c_{je}^{out} - c_{je}^{in} = i2\sqrt{\pi} g_j c_j, (j = 1, 2, 3). \quad (9)$$

Performing the Fourier transformations $F(\Delta_1) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} f(t)e^{i\Delta_1 t} dt$ on Eq. 3(c) and Eq. 8(a), substituting c_j into Eq. (9), and using the scattering matrix of the Sagnac interferometer [38, 39] when $\Omega_3 = 0$, we can get the transport properties as

$$T_1(\Delta_1) = \frac{c_{1e}^{out}}{c_{1e}^{in}} = 1 - \frac{2\Gamma_1(i\Delta_1 A_2 + \Omega_2^2)}{A_1(i\Delta_1 A_2 + \Omega_2^2) + \Omega_1^2 A_2}, \quad (10a)$$

$$T_2(\Delta_1) = \frac{c_{2e}^{out}}{c_{2e}^{in}} = \frac{2\sqrt{\Gamma_1 \Gamma_2} \Omega_1 \Omega_2}{A_1(i\Delta_1 A_2 + \Omega_2^2) + \Omega_1^2 A_2}, \quad (10b)$$

$$T_3(\Delta_1) = \frac{c_{3e}^{out}}{c_{3e}^{in}} = 0, \quad (10c)$$

where $A_j = i\Delta_1 + \Gamma_j + \gamma_j/2$ and $\Gamma_j = 2\pi g_j^2$ ($j = 1, 2, 3$). For the case $\Delta_1 = 0$ and $\Omega_j \neq 0$ ($j = 1, 2, 3$), we have

$$T_1(\Delta_1) = 1 - \frac{2\Gamma_1(\Gamma_2' \Omega_3^2 + \Gamma_3' \Omega_2^2)}{\Gamma_2' \Gamma_3' \Omega_1^2 + \Gamma_1' \Gamma_2' \Omega_3^2 + \Gamma_1' \Gamma_3' \Omega_2^2}, \quad (11a)$$

$$T_2(\Delta_1) = \frac{2\sqrt{\Gamma_1 \Gamma_2} \Omega_1 \Omega_2 \Gamma_3'}{\Gamma_2' \Gamma_3' \Omega_1^2 + \Gamma_1' \Gamma_2' \Omega_3^2 + \Gamma_1' \Gamma_3' \Omega_2^2}, \quad (11b)$$

$$T_3(\Delta_1) = \frac{2\sqrt{\Gamma_1 \Gamma_3} \Omega_1 \Omega_3 \Gamma_2'}{\Gamma_2' \Gamma_3' \Omega_1^2 + \Gamma_1' \Gamma_2' \Omega_3^2 + \Gamma_1' \Gamma_3' \Omega_2^2}, \quad (11c)$$

where $\Gamma_j' = \Gamma_j + \gamma_j/2$ ($j = 1, 2, 3$). The transmission coefficient $T_j(\Delta_1)$ corresponds to the j th output pulse. In the present scheme, selective frequency conversion is based on the selection of classical cw fields. As shown in Fig. 1(b), for instance, when the cw Ω_j ($j = 1, 2, 3$) is cutoff, the output quantum field g_j is also forbidden. The condition $\Omega_3 = 0$ leads to Eqs. 10, which indicates that the frequency of the input quantum field g_1 may be converted from $\omega_{10} - \Delta_1$ into $\omega_{20} - \Delta_2$ through adjusting parameters.

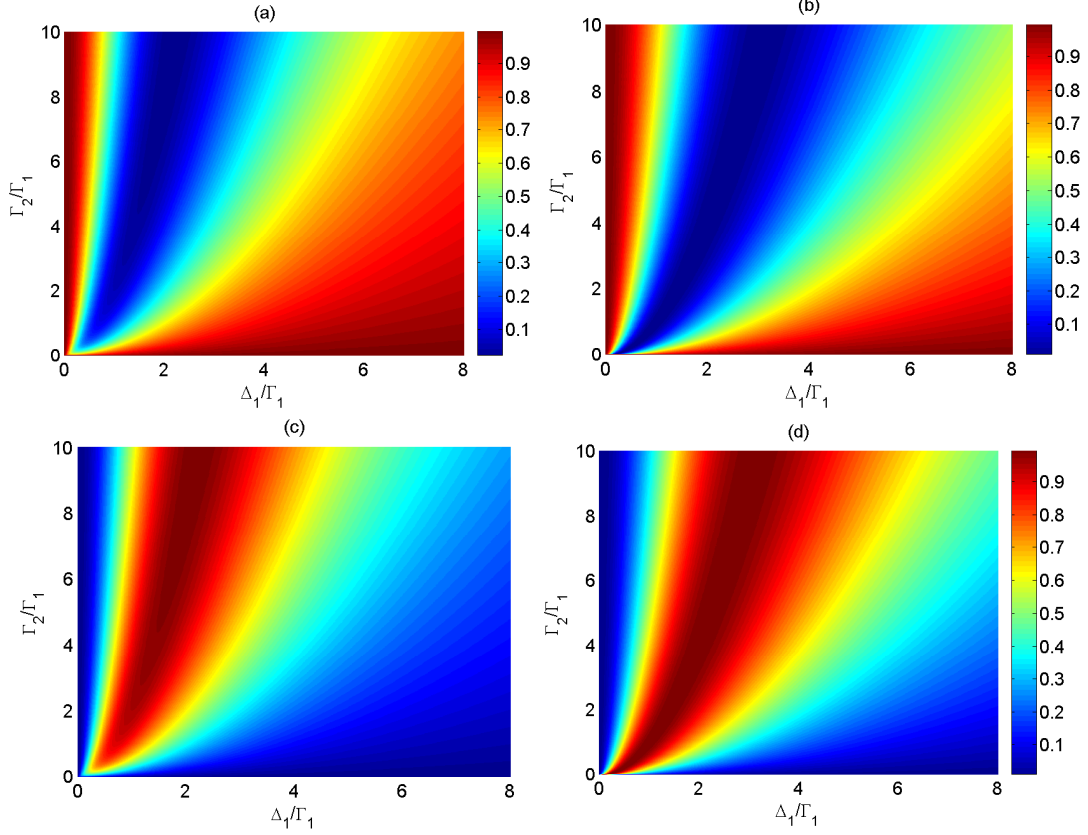


FIG. 2: (Color online) The transport properties versus Γ_2/Γ_1 and Δ_1/Γ_1 . $|T_1(\Delta_1)|^2$ with (a) $\Omega_1 = \Omega_2/\sqrt{2} = \Delta_1$ and (b) $\Omega_1 = \Omega_2 = \Delta_1$; $|T_2(\Delta_1)|^2$ with (c) $\Omega_1 = \Omega_2/\sqrt{2} = \Delta_1$ and (d) $\Omega_1 = \Omega_2 = \Delta_1$.

III. ANALYSIS AND DISCUSSION

For simplicity, we consider first the case of $\gamma_j = 0$. By studying Eqs. 10(a)-(b), we can try to find the appropriate parameters which lead to perfect frequency conversion. When parameters satisfy the following conditions

$$(\Omega_1^2 - \Delta_1^2)\Gamma_2 + (\Delta_1^2 - \Omega_2^2) = 0 \quad (12a)$$

$$\Delta_1(\Omega_1^2 + \Omega_2^2 - \Gamma_1\Gamma_2 - \Delta_1^2) = 0, \quad (12b)$$

the efficiency of quantum frequency conversion reaches unity, i.e., $|T_1(\Delta_1)|^2 = 0$ and $|T_2(\Delta_1)|^2 = 1$. It is easy to find that we can obtain wonderful frequency conversion not only for resonant case but also for off-resonant case. For example, the condition $\Omega_1^2\Gamma_2 = \Omega_2^2\Gamma_1$ ensures the complete frequency conversion for the resonant case $\Delta_1 = 0$. More generally, we further described the effect of parameters on the transport properties in Fig. 2(a)-(d), which show that the efficiency near unity is achievable with frequency detuning and coupling strengths $\Gamma_j (j = 1, 2)$ in a wide region.

Spontaneous decay of the atomic excited states will seriously influence the efficiency of quantum frequency conversion. As shown in Fig. 3, the converted probability of photon $|T_2(\Delta_1)|^2$ declines dramatically as the decay rates increase. In the meantime the loss probability of photon P_{loss} increases sharply. Nevertheless, even then we can get the converted probability $|T_2(\Delta_1)|^2$ more than 86% with $\gamma_1 \simeq \gamma_2 = 0.2\Gamma_1$. In addition, the converted probability $|T_2(\Delta_1)|^2$ and loss probability P_{loss} reach maximum at the resonant point with the parameters $\Gamma_2 = \Omega_1 = \Omega_2/\sqrt{2} = 2\Gamma_1$, which just satisfy the above condition $\Omega_1^2\Gamma_2 = \Omega_2^2\Gamma_1$ for the resonant case. The probability $|T_1(\Delta_1)|^2$, however, is not obviously affected by the dissipation, and is nearly zero at resonant point for different decay rate.

The present scheme under consideration is capable of generating mode entanglement of photons. From Eqs. 10, we can find that the maximum mode entanglement of two photons can be realized by adjusting parameters until $|T_1(\omega)|^2 = |T_2(\omega)|^2 = 1/2$. In the following discussion, we focus on generation of the W entangled state of photons of different frequencies. For simplicity, we consider only the resonant case, i.e., $\Delta_1 = 0$ and obtain the transport properties as described in Eqs. 11. The parameters conditions $\Gamma_2 = \Gamma_3$, $\Omega_2 = \Omega_3$ and $\Omega_2/\Omega_1 = (\sqrt{3} - 1)\sqrt{\Gamma_2/\Gamma_1}/2$ will lead to $|T_1(\omega)|^2 = |T_2(\omega)|^2 = |T_3(\omega)|^2 = 1/3$. In this

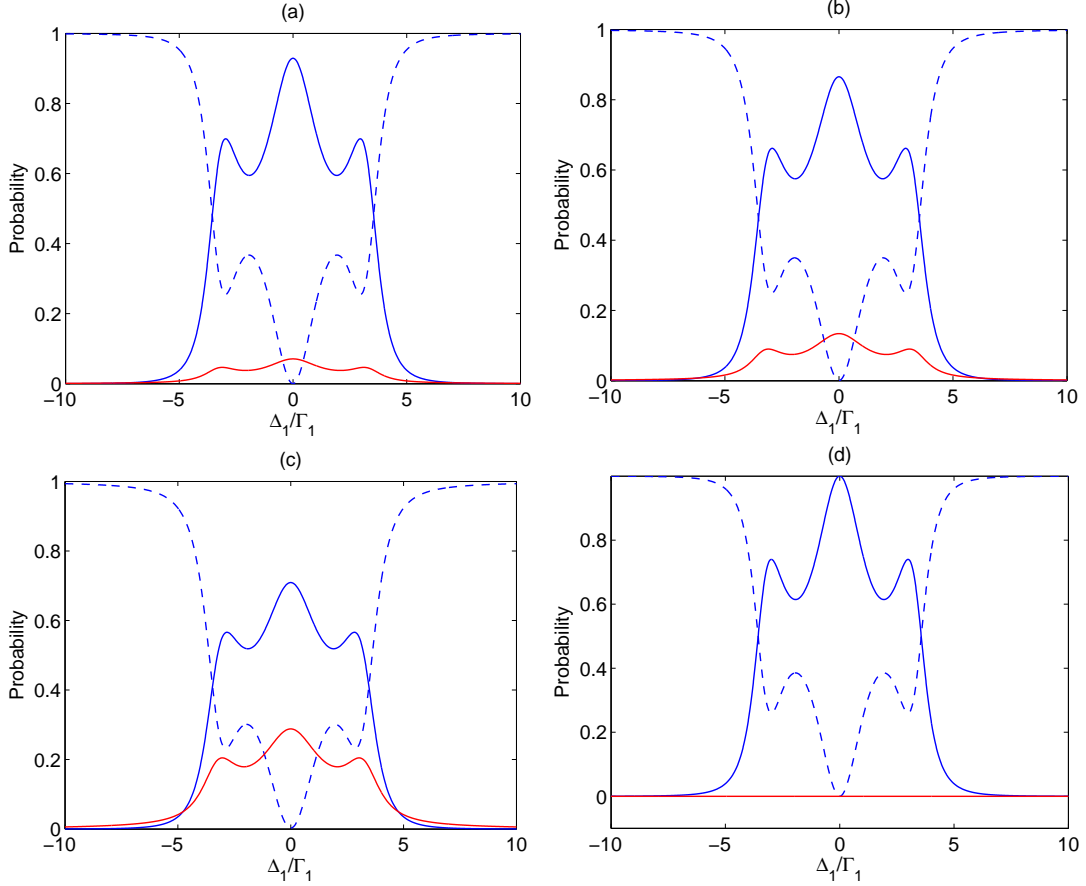


FIG. 3: (Color online) Probability $|T_1(\Delta_1)|^2$ (blue dash lines), $|T_2(\Delta_1)|^2$ (blue solid lines) and loss probability of photon $P_{loss} = 1 - |T_1|^2 - |T_2|^2$ (red solid lines) versus frequency detuning Δ_1/Γ_1 with (a) $\gamma_1 = 0.1\Gamma_1$; (b) $\gamma_1 = 0.2\Gamma_1$; (c) $\gamma_1 = 0.5\Gamma_1$; (d) $\gamma_1 = 0$; Other parameters are chosen as $\Gamma_2 = \Omega_1 = \Omega_2/\sqrt{2} = 2\Gamma_1$ and $\gamma_2 \approx \gamma_1$.

case, the output pulses are in the standard W entangled state, i.e., $|\psi\rangle_w = \frac{1}{\sqrt{3}}(|1_{\omega_{10}}00\rangle + |01_{\omega_{20}}0\rangle + |001_{\omega_{30}}\rangle)$. Here, the states $|1_{\omega_{10}}00\rangle$, $|01_{\omega_{20}}0\rangle$ and $|001_{\omega_{30}}\rangle$ correspond to transport pulses $|T_1(\omega)|^2$, $|T_2(\omega)|^2$ and $|T_3(\omega)|^2$, respectively. In fact, by choosing intensities of cw properly, one can obtain different transport properties $|T_j(\omega)|^2$ ($j = 1, 2, 3$). To be clear, we describe the changes of transport properties $|T_j(\omega)|^2$ ($j = 1, 2, 3$) and fidelity of entangled states with different experimental parameters in Fig. 4(a)-(b), which show the present scheme has flexible adjustment of parameters. In addition, we consider the effect of decay rate on the fidelity of W entangled state in Fig. 4(c). When $\gamma/\Gamma_1 = 0.5$, the fidelity F of the W of photons of three kinds of frequencies is more than 91%.

In the above analysis, we have carried out extensive numerical calculations to establish the validity of the present scheme by experimentally achievable parameters. Cold ^{87}Rb atoms can be chosen as a possible experimental candidate system for the present scheme. We take, for example, $|0\rangle = |5S_{1/2}, F = 1\rangle$, $|e\rangle = |5S_{1/2}, F = 2\rangle$, $|1\rangle = |5P_{3/2}, F = 0\rangle$, $|2\rangle = |5P_{3/2}, F = 1\rangle$ and $|3\rangle = |5P_{3/2}, F = 2\rangle$, which correspond to the multi- Λ configuration shown in Fig. 1(b). The appropriate transitions are $|0\rangle \rightleftharpoons |j\rangle$ and $|e\rangle \rightleftharpoons |j\rangle$ ($j = 1, 2, 3$) with $\gamma_{je} = \gamma_{j1} = \gamma_j/2 = 2\pi \times 6 \text{ MHz}$. Notice that some works are based on a three-level and multi- Λ system, including four-wave mixing [25, 28] and induced transparency [40]. As shown in Fig. 1(c), a three-state and multi- Λ system is suitable for the present scheme. We can also get the same result through the process similar to the above.

To summary, we propose a theoretical scheme for selective quantum frequency conversion and multifrequency mode entanglement via input-output formalism. The frequency of the output photon can be selected by applying proper classical fields. The probability amplitudes of the output photons also can be adjusted by choosing intensities of driving fields and other experimental parameters properly. The adjustable probability amplitudes will lead to the generation of multifrequency mode W entanglement. Even for the existence of spontaneous decay of excited states, we can obtain the highly efficient frequency conversion and multifrequency mode W entanglement with high fidelity. In addition, our calculations show that the present scheme can work well in a wide parameters region.

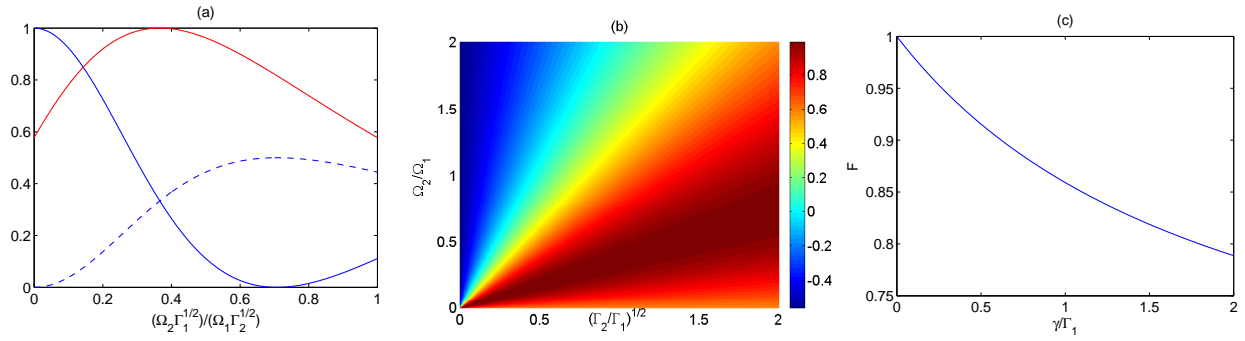


FIG. 4: (Color online) (a) The fidelity of photonic entanglement F (red solid lines) and the probability $|T_1(\omega)|^2$ (blue solid lines), $|T_2(\omega)|^2 = |T_3(\omega)|^2$ (blue dash lines) as functions of $(\Omega_2 \Gamma_1^{1/2})/(\Omega_1 \Gamma_2^{1/2})$ and Δ_1/Γ_1 with $\Omega_2 = 2(2 - \sqrt{2})\Gamma_1$; (b) The fidelity F of the W entanglement of three frequency modes against Ω_2/Ω_1 and $\Gamma_2^{1/2}/\Gamma_1^{1/2}$; (c) The fidelity F against decay rate γ/Γ_1 with $\gamma \simeq \gamma_j$ ($j = 1, 2, 3$) and $\Omega_2/\Omega_1 = (\sqrt{3} - 1)\sqrt{\Gamma_2/\Gamma_1}/2$; Other parameters are $\Omega_2 \simeq \Omega_3$ and $\Gamma_2 \simeq \Gamma_3$.

Acknowledgments

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